

Magnetization switching by ultrashort acoustic pulses

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It is shown theoretically that a single a few picoseconds long acoustic pulse can reverse magnetization in a magneto-strictive material Terfenol-D. Following giant magneto-elastic changes of free energy density the magnetization vector is kicked out of a local in-plane energy minimum and decays into another minimum. For acoustic pulse duration significantly shorter than magnetization precession period $\tau_{ac} \ll T_{prec}$, the switching threshold is determined by the *acoustic pulse area*, i.e. pulse integral in time domain, similar to coherent phenomena in optics. Simulation results are summarized in a magneto-acoustic switching diagram and discussed in the context of all-optical magnetization switching by circularly polarized light pulses.

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Searching for new possibilities of ultrafast magnetization switching is motivated by continuously growing demand in faster data recording technologies, which are based on reversal of individual magnetic bits at the nano-scale. Among different mechanisms of magnetization switching the acoustically driven switching at ultrafast time scales remains largely unexplored.

The first pioneering time-resolved observation of magnetization dynamics in ferromagnetic nickel induced by femtosecond laser pulses revealed the phenomenon of ultrafast demagnetization in nickel [1]. The ultrafast drop of magnetization on a sub-picosecond time scale was caused by transient elevation of electron temperature close to the Curie point. The subsequent dynamics of magnetization recovery on a time scale exceeding tens of picoseconds could be adequately reproduced by Landau-Lifshitz-Gilbert (LLG) equations describing damped precession of magnetization vector in the presence of temperature-dependent magneto-crystalline anisotropy [2].

The most recent experiments combining picosecond acoustics [3] with ultrafast magneto-optics showed that the magneto-crystalline anisotropy can be also changed by picosecond acoustic strain pulses to a ferromagnetic semiconductor GaMnAs [4, 5] or nickel [6], thus triggering the magnetization precession without heating the sample. However, due to the relatively small magneto-strictive coefficient in GaMnAs ($\Lambda \sim 10^{-5}$ at cryogenic temperature [7]) and nickel ($\Lambda \sim 3 \times 10^{-5}$ at room temperature [8]), the resulting transient change in magnetization direction appeared to be too small and the magnetization vector returned to its initial direction, i.e. magnetization switching (reversal) did not occur.

The first experimental demonstration of ultrafast *non-thermal* magnetization switching was reported in 1998 by Back and co-workers [9], who used ultrashort pulses of magnetic field induced by relativistic electron bunches to switch magnetization in Co/Pt film. Most recently a spectacular observation of all-optical magnetization

switching in GdFeCo using circularly polarized light pulses [10, 11], raised a lot of questions about physically unclear switching mechanisms suggesting that not only transient overheating of electrons but also the dynamics of lattice temperature may be necessary to explain the underlying physics [12]. Not only the minimum amount of deposited heat [12] but also a minimum amount of 'circularity' was necessary to obtain switching [13], at least within a certain range of optical excitation [14].

In this letter we theoretically investigate the interaction of ultrashort acoustic pulses with Terfenol-D ($\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$), the rare-earth compound famous through its giant magneto-strictive coefficient $\Lambda \sim 10^{-3}$ [8], and demonstrate the possibility of ultrafast magneto-acoustic switching. Moreover, the results are discussed within the framework of recently observed all-optical magnetization switching by single circularly polarized femtosecond laser pulses, which is undoubtedly accompanied by the generation of picosecond pulses of coherent acoustic phonons [3].

The phenomenological expression for free energy density $F(\vec{M}) = F_k + F_{me} + F_d + F_z$ for (110) thin films of $\text{Tb}_{0.27}\text{Dy}_{0.73}\text{Fe}_2$ epitaxially grown on sapphire reads [15]:

$$F_k = K_1(\alpha_x^2\alpha_y^2 + \alpha_x^2\alpha_z^2 + \alpha_z^2\alpha_y^2) + K_2(\alpha_x^2\alpha_y^2\alpha_z^2) \quad (1)$$

$$F_{me} = b_1(\alpha_x^2e_{xx} + \alpha_y^2e_{yy} + \alpha_z^2e_{zz}) + b_2(\alpha_x\alpha_y e_{xy} + \alpha_x\alpha_z e_{xz} + \alpha_y\alpha_z e_{yz}) \quad (2)$$

$$F_d = \frac{\mu_0}{2}(M_s \cos \theta)^2, \quad (3)$$

where $\alpha_x, \alpha_y, \alpha_z$ are direction cosines of the magnetization vector $\vec{M} = M_s(\alpha_x, \alpha_y, \alpha_z)$ in the crystallographic coordinate system (x, y, z) and saturation magnetization $\mu_0 M_s = 0.945$ T. In the rotated frame (x', y', z') the direction of magnetization is determined by two angles θ (out-of-plane angle) and ϕ (in-plane angle), see Fig. 1(a). In Eq. (1-3) F_k , F_{me} and F_d denote the magneto-crystalline anisotropy, magneto-elastic and magneto-static terms, respectively, and Zeeman contribution $F_z = -\mu_0 \vec{H}_{ext} \vec{M}$ is disregarded through out this

paper as we consider the case of zero external magnetic field, $\vec{H}_{ext} = 0$.

Epitaxial growth of a thin Terfenol-D film in (110) direction on a lattice-mismatched substrate induces the built-in static strain described by the following tensor:

$$e_{stat} = \begin{pmatrix} 0 & e_{xy} & 0 \\ e_{xy} & 0 & 0 \\ 0 & 0 & -\frac{2c_{12}}{c_{11}}e_{xy} \end{pmatrix}, \quad (4)$$

which is determined by a single strain component $e_{xy} = -0.55\%$ [16] in a crystallographic coordinate frame (x, y, z) (Fig. 1(a)). The competition of different contributions in the total free energy density results into four local in-plane energy minima corresponding to four different magnetization directions 1,2,3,4 in Fig. 1(b). The explicit dependence of the magneto-elastic term F_{me} both on the strain components and magnetization direction and large values of magneto-elastic coupling coefficients $b_1 = -\frac{3}{2}\Lambda_{100}(c_{11} - c_{12}) = -80$ MPa and $b_2 = -3\Lambda_{111}c_{44} = -85$ MPa [17] suggest that application of external strain will shift the minima of free energy minima and therefore, change the magnetization direction. Indeed, the application of time-independent uniaxial strain η in the direction normal to the surface of a thin Terfenol-D film results into the in-plane shift of all four energy minima by the angle $\Delta\Phi$, as illustrated in Fig. 1(c) for $\eta = -0.3\%$ (film compression) and $\eta = 0.9\%$ (film tension).

The action of a time-dependent uniaxial strain (acoustic pulse) $\eta(t)$ can be described by adding the following dynamic tensor in a crystallographic coordinate frame

$$e_{dyn}(t) = \frac{1}{2} \begin{pmatrix} \eta(t) & -\eta(t) & 0 \\ -\eta(t) & \eta(t) & 0 \\ 0 & 0 & 0 \end{pmatrix}, \quad (5)$$

where the rotation of coordinates system by 45° from (x', y', z') into (x, y, z) leads to factor 1/2 and generates the non-diagonal terms.

Inserting the total strain $e(t) = e_{stat} + e_{dyn}(t)$ in Eq. (2) generates explicit time-dependence of free energy $F(t)$, which drives the magneto-acoustic dynamics described by LLG equation [6]

$$\frac{d\vec{M}}{dt} = -\gamma\mu_0(\vec{M} \times \vec{H}_{eff}) + \frac{\alpha}{M_s} \left(\vec{M} \times \frac{d\vec{M}}{dt} \right) \quad (6)$$

where the first term describes the torque driving the precession of magnetization vector around the effective time-dependent magnetic field $H_{eff}(t)$

$$\vec{H}_{eff}(t) = -\frac{1}{\mu_0} \frac{dF(t)}{d\vec{M}} \quad (7)$$

and the second term describes precession damping according to the phenomenological Gilbert damping parameter $\alpha = 0.1$ [18]; γ is the gyromagnetic ratio.

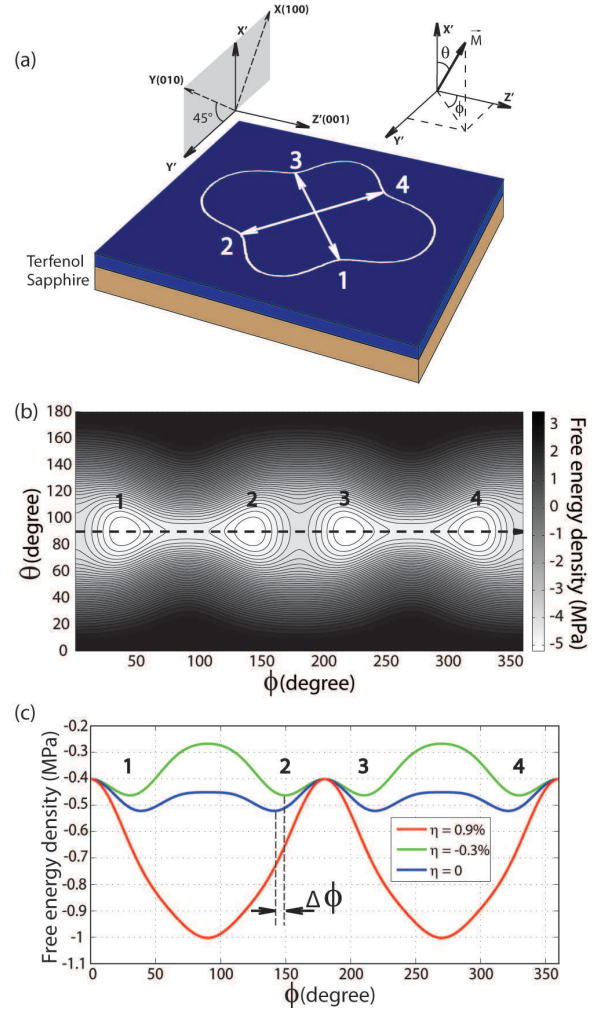


FIG. 1: Magneto-elastic free energy density in a thin (110) film of Terfenol-D grown on sapphire (a) possesses four in-plane energy minima (b). Application of a *static* uniaxial compressive ($\eta = -0.3\%$) or tensile ($\eta = 0.9\%$) strain in the direction perpendicular to the film leads to the in-plane shift $\Delta\Phi$ of all four energy minima (c).

If the system is initially prepared in minimum 2, the application of instantaneous step-like strain [19] results into damped precession of magnetization vector into the new minimum 2' with a precession period $T_{prec} \simeq 25$ ps, see Fig. 2. However, if the strain is turned off after some time, the situation equivalent to the application of a rectangular acoustic pulse of finite duration τ_{ac} , the precession trajectory will decay back into minimum 2. Such magneto-acoustic precession trajectory induced by the action of a picosecond acoustic pulse with $\tau_{ac} = 3$ ps and strain amplitude $\eta_{ac} = 3 \times 10^{-3}$ is shown in Fig. 2 and can be explained analytically.

LLG equations (6) for the initial condition in one of the four energy minima read

$$\frac{d\phi}{dt} = 0, \quad \frac{d\theta}{dt} = \gamma \frac{(b_2 + 2b_1)}{2M_s} \alpha'_y \alpha'_z \eta(t) \quad (8)$$

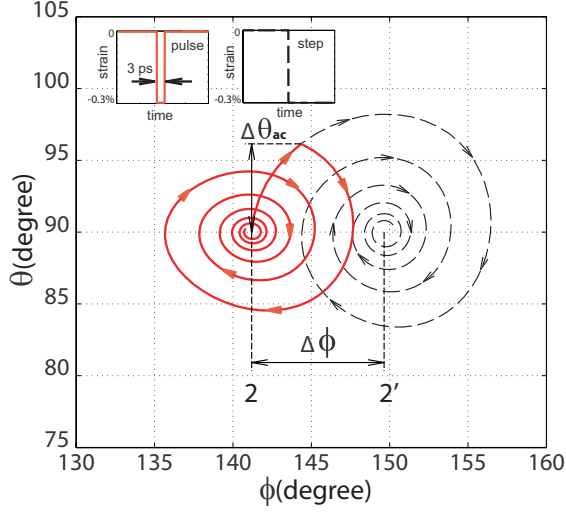


FIG. 2: Starting from energy minimum 2, a *dynamic* step-like strain induces a damped magnetization precession around the shifted minimum 2' (dashed line). An ultrashort acoustic pulse results into the out-of-plane kick $\Delta\theta_{ac}$ followed by damped precession into the initial minimum 2 (continuous line).

and their integration for an ultrashort acoustic pulse $\eta(t)$ obeying the condition $\tau_{ac} \ll T_{prec}$ approximate well the acoustic *out-of-plane* kick of the magnetization vector by the angle

$$\Delta\theta_{ac} \simeq \gamma \frac{(b_2 + 2b_1)}{2M_s} \alpha'_y \alpha'_z \int \eta(t) dt. \quad (9)$$

The product of directional cosines $\alpha'_y \alpha'_z$ in Eq. (9) equals 0.48 for energy minima 1 and 3 and -0.48 for two other minima, respectively. Therefore, depending on the initial condition, the same acoustic pulse will kick the magnetization vector out of sample plane in opposite directions. Equation (9) clarifies the microscopic physical model beyond the time-dependent magnetic torque $|\vec{M} \times \vec{H}_{eff}|$ introduced by Kim and co-workers [6] and shows that the prefactor in Eq. (9) is dominated by the ratio of magneto-elastic coupling coefficients b_1 and b_2 (which are both proportional to the respective coefficients of magnetostrictive tensor Λ) to saturation magnetization M_s .

Similar to polarization dynamics in coherent optics, the acoustic rotation angle $\Delta\theta_{ac}$ of magnetization vector appears to be proportional to the *acoustic pulse area* $\int \eta(t) dt$ for arbitrary acoustic pulses obeying $\tau_{ac} \ll T_{prec} \simeq 25$ ps. It suggests that the so-called bi-polar acoustic pulses generated at free metal-air interfaces [3] are particularly inefficient in magneto-acoustics since positive and negative parts in a bi-polar pulse cancel each other giving zero acoustic pulse area. Recently observed large-amplitude unipolar acoustic pulses with 3 ps duration and amplitudes up to 1% generated in a thin cobalt transducer sandwiched between dielectric substrate and

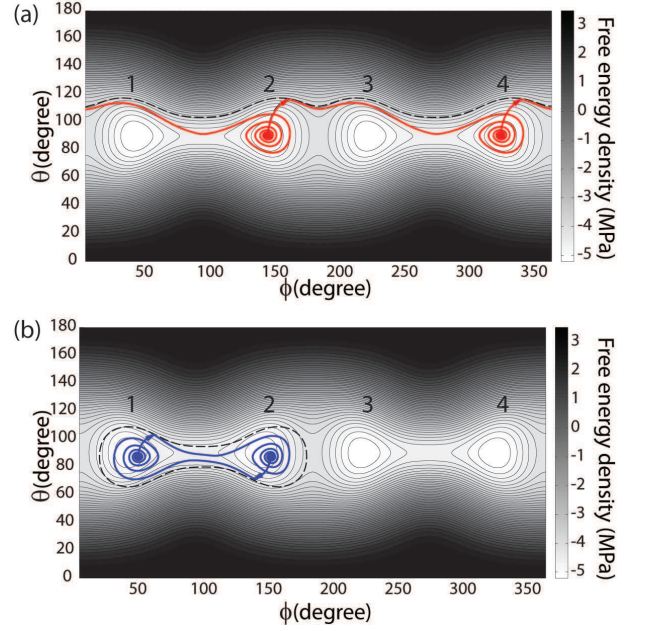


FIG. 3: After application of large-amplitude 3 ps long acoustic pulse the magnetization vector initially prepared in state 2 will decay (switch) into one of the neighboring energy minima. (a) a sequence of compressional pulses with $\eta_{ac} = -1.6\%$, induces the clock-wise rotation of magnetization vector: $2 \rightarrow 4$, $4 \rightarrow 2$, etc. (b) a sequence of tensile pulses with $\eta_{ac} = 0.9\%$ results into repetitive switching between two adjacent energy minima: $2 \rightarrow 1$, $1 \rightarrow 2$, etc. Dashed contours show the magnetization trajectories after excitation by a single pulse in the absence of damping.

a layer of noble metal [20, 21] are better suited for experimental investigations in coherent magneto-acoustics.

When using rectangular unipolar acoustic pulses the kick angle $\Delta\theta_{ac}$ is proportional to the product $\eta_{ac} \times \tau_{ac}$ and thus can be increased by using larger strain amplitude η_{ac} or somewhat longer pulse duration $\tau_{ac} \ll T_{prec}$.

Figure 3 shows that both compressional ($\eta_{ac} < 0$, Fig. 3a) or tensile ($\eta_{ac} > 0$, Fig. 3b) rectangular unipolar acoustic pulses with $\tau_{ac} = 3$ ps are capable of switching the initial magnetization direction into the new minimum, which represents the main result of this paper. For example, a three picosecond long compressional pulse with strain amplitude 1.6% switches the magnetization from minimum 2 into minimum 4 ($2 \rightarrow 4$, see Fig. 3a). Application of a consequent identical compressional pulse bring the magnetization back into minimum 2 ($4 \rightarrow 2$, suggesting that a pulse train will result into clock-wise rotation of magnetization vector. In contrast, a sequence of 3 ps long tensile strain pulses will periodically switch the magnetization between minima 2 and 1 ($2 \rightarrow 1$ and $1 \rightarrow 2$ see Fig. 3b).

Therefore the results of our simulations suggest that a clean experimental demonstration of magneto-acoustic switching would necessarily imply a single-shot experi-

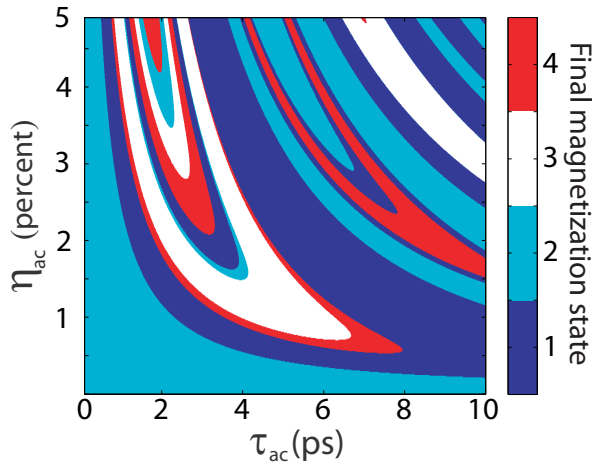


FIG. 4: Diagram of magneto-acoustic switching. Depending on the duration τ_{ac} and amplitude η_{ac} of a unipolar tensile acoustic pulse, the magnetization vector initially prepared in state 2 undergoes the transition $2 \rightarrow 1$ (dark blue area), $2 \rightarrow 4$ (red area), $2 \rightarrow 3$ (white area) or $2 \rightarrow 2$ (no switching, light blue area).

ment where the magnetic system is prepared in the same state before the action of the consequent acoustic pulse.

The typical kick angle required for switching is about 20° and the different threshold switching amplitudes and pathways for tensile and compressive pulses are caused by different height of the potential barrier between the neighboring energy minima. The more general phase diagram for magneto-acoustic switching is shown in Fig. 4, where the boundaries between different switching zones generally follow the $1/\tau_{ac}$ dependence, in agreement with the assumption that primarily the amplitude of out-of-plane acoustic kick $\Delta\theta_{ac} \sim \eta_{ac} \times \tau_{ac} = \text{const}$ determines the switching pathway. Similar analysis for the acoustic shear pulses leads to the same conclusions, in particular with respect to the acoustic pulse area and dependence of the switching amplitude on the acoustic pulse duration.

It is quite remarkable that the threshold fluence for all-optical magnetization switching in a rare-earth compound GdFeCo induced by a single circularly polarized pump pulse almost does not depend on the optical pulse duration [12]. Longer optical excitation leads to longer acoustic pulses [22], which are generated by thermo-elastic expansion of laser-heated GdFeCo. The analysis of thermo-elastic generation mechanism by longer optical pulses suggests that the absorbed laser fluence is proportional to the product of acoustic pulse amplitude by its duration, i.e. to the acoustic pulse area. Therefore, the observed constant threshold fluence for all-optical magnetization switching in GdFeCo could be explained by magneto-elastic mechanism. From the magneto-acoustic point of view a significantly lower magnetostriction coefficient $\Lambda \sim 10^{-5}$ in GdFeCo [23] is balanced by a much lower room temperature saturation magnetization

$\mu_0 M_s \simeq 8$ mT close to the compensation point [10], thus giving the same order-of-magnitude prefactor Λ/M_s in Eq. (9). The observed increase of switching fluence in GdFeCo with temperature [13] is consistent with the decrease of Λ/M_s in rare-earth compounds for higher temperatures [15]. Therefore, despite of being far away from quantitative modeling, all these arguments corroborate the hypothesis [20] that ultrashort acoustic phonon pulses may play an important role in the dynamics of all-optical magnetization switching in GdFeCo [10, 11]. Moreover, possible magneto-elastic contributions of helically polarized acoustic shear pulses excited by circularly polarized electromagnetic pulses [24, 25] may solve the puzzle of an undefined long-living reservoir for angular momentum as highlighted in the most recent systematic investigations [12, 13].

To summarize, in this letter we have theoretically predicted the new mechanism of ultrafast *non-thermal* magneto-acoustic switching in Terfenol-D. This phenomenon may open the door to ultrafast magnetic recording not relying on heating the magnetic material close the Curie point.

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